

# Tensile Testing of the Transport Solenoid for the Mu2e Experiment at Fermilab



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## Abstract

The Mu2e experiment at Fermilab seeks to measure the rare process of direct muon to electron conversion in the field of a nucleus. The magnet system for this experiment is made up of three solenoids: the production solenoid, the transport solenoid and the detector solenoid. The transport solenoid is an S-shaped solenoid set between the other big solenoids serving as a connection chamber between them. In this paper, details of the tensile test carried out on twelve samples forged from the aluminum cylinder for the transport solenoid is discussed, to ascertain relevant mechanical and physical properties in order to meet field specifications.

## Introduction

The muon to electron (Mu2e) experiment at Fermilab is a project that aims to explore physics beyond the standard model by seeking direct muon to electron conversion in the field of a nucleus. Of the three solenoids that make up the magnet system of this experiment, the transport solenoid (TS) is of specific interest in this paper.

The Transport Solenoid is an S-shaped 13m long solenoid whose main objective is to transport the muons created by a proton hitting a target inside the production solenoid to the stopping target in the detector solenoid.

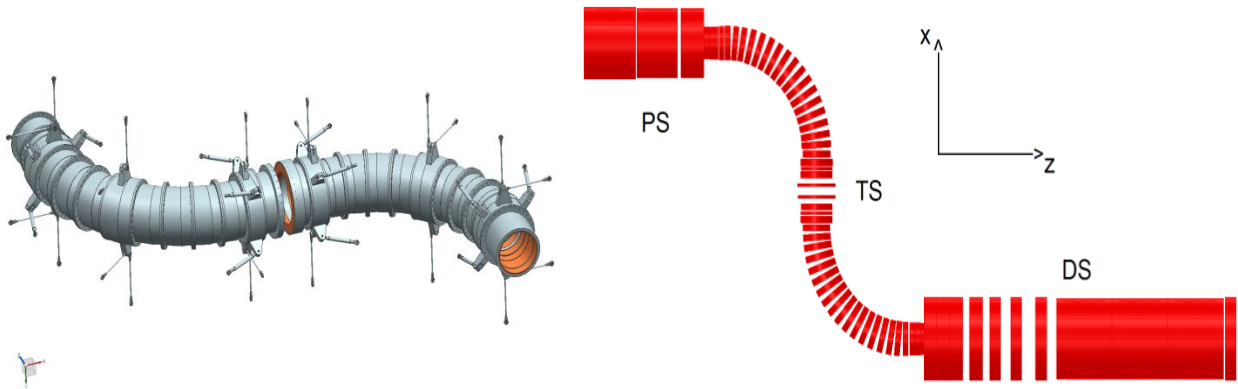


Figure 1: Global model for the Transport Solenoid.

## Methods

The transport solenoid coils were wound on collapsible mandrels shrink fitted into aluminum shells and then combined together into a single cold mass and power unit. The shells are manufactured from forged cylinders made of aluminum alloy (Al 5083-O) bored at both ends to make room for the coils.

A total of 24 sample pieces were cut out from an 8mm slice of forged aluminum cylinder. The cut slice was divided into 4 quadrants and each quadrant had 6 test pieces cut out from it. All test samples were milled and machined to ASTM<sup>1</sup> specifications and were carefully labeled.

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<sup>1</sup> American Society for Testing and Materials

## **Problem**

Previously, 12 of the 24 samples have been destructively tested, but results from these tested samples indicated that the material properties of the aluminum cylinder were below the range of values as estimated on the ASME<sup>2</sup> standards. Five of the twelve samples turned out to be mechanically weaker in terms of yield strength, and it was suggested that these material failure might have been caused by several factors such as forging error or a problem with the Instron machine used to carry out this tensile test. However, the case of a forging error was soon ruled out as most material properties such as the yield strength increases after forging. Therefore, the task was to make necessary adjustment on the Instron machine and carry out a tensile test on the remaining 12 samples to determine different material properties such as its yield strength, the Young's modulus and the ultimate tensile strength.

## **Tensile testing and the Instron machine**

The tensile test measures the resistance of a material to a static or slowly applied force. Tensile testing helps to understand the tensile properties of a material which are used to predict the behavior of the material under forms of loading. Tensile properties help to predict the strength of the material and are used to determine material specification to ensure quality.

### **Tensile Testing Equipment**

The Instron machine is the mechanical testing machine used to carry out uniaxial tensile test (a test which involves gripping a specimen at both ends and subjecting it to increasing axial load until it breaks). It is used to produce the desired specimen loading through static load cells and has grips where specimen can be fitted to carry out the test.

The Extensometer is an instrument used for determining at any time the distance between two fixed points located within the gage length of the test specimen when the load is applied. With the extensometer coupled with the load recorder, a stress-strain curve is obtained of the load as a function of deformation

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<sup>2</sup> American Society of Mechanical Engineers

Load Cells (part of the Instron machine) are used to measure the load applied to the specimen and transmit the signal to the control console where it is conditioned for display, data collection and control.

Test Specimen is the sample of the material to be tested. It must be from the same source and must have undergone the same processing steps. Standard test specimen specification as stated in ASTM standard documentation must be followed when fabricating the test specimens to ensure accurate results.

Series IX software is the computer program that records, stores and calculates all data obtained from the tensile test.

Micrometer Screw Gauge is used to measure raw data such as the diameter of specimen before and after breaking, cross sectional area of specimen before testing and all types of measurement necessary to obtain desired parameters.

### **Material Properties obtained from the Tensile Test**

**Yield Strength:** This is the stress at which plastic deformation becomes noticeable. It is the stress that divides the plastic behavior and the elastic behavior of the material. In some materials, the stress at which the material changes from elastic to plastic behavior is not easily noticeable. In this case we determine offset yield strength, by constructing a line parallel to the initial portion of the stress-strain curve but with an offset of 0.002 in. (0.2%) from the origin. The 0.2% offset yield strength is the stress at which our constructed line intercepts the stress-strain curve.

**Tensile Strength:** This is the stress obtained at the highest applied force. It is the maximum stress on the engineering stress-strain curve. It is also the stress at which necking begins in ductile materials.

**The Modulus of Elasticity:** This is the slope of the stress-strain curve in the elastic region. It is a measure of the stiffness of the material.

**Ductility:** Ductility measures the amount of deformation that a material can withstand without breaking.

$$\%Elongation = \frac{L_f - L_0}{L_0} \times 100$$

Where  $L_f$  and  $L_0$  which are the final and initial gage lengths of the test specimen respectively are obtained from the gage marks of the extensometer

$$\%Reduction\ in\ Area = \frac{A_0 - A_f}{A_0} \times 100$$

$A_0$  and  $A_f$  are the initial and final CSA after fracture respectively

Effect of Temperature: Yield strength, Tensile strength and Elasticity all decrease at high temperatures but ductility increases.

### **Notable Adjustment.**

The test that was carried out on the first 12 samples was done without an extensometer and the strain was directly measured by the Instron machine which might have been the reason for the failure observed on those samples, therefore for this experiment an extensometer with a gage length of 1 inch was used to measure the strain as the test was been carried out.

### **Results.**

The previously tested 12 samples were destructively tested, that is, testing continued until break point, but for the 12 samples I tested, I carried out a non-destructive tensile test on them and the test was stopped mid-way through the plastic region as we are interested in the material properties in the elastic region. Due to some problem with calibration and setting the most effective parameters for the tensile test, the result for the first sample (Q1R2) was inconsistent and has not been included in this report. The samples were labeled in accordance with the portion of the cylinder from which they were cut. Q stands for quadrant, R for radial direction and A for axial direction. There are four quadrants in all, two radial directions and four axial directions and for example Q1R2 stands for, first quadrant along the second radial direction.

All Samples	Load at Peak (lbs)	% Strain at Peak	Yield Strength (psi)	Young's Modulus (ksi)	
Q1R2	****	****	****	****	
Q2R2	1179	0.534	18910	9658	
Q3R2	1178	0.525	19165	10749	
Q4R2	1192	0.542	19427	10618	
Q1A3	1236	0.543	19856	8520	
Q2A3	1244	0.531	20247	9519	
Q3A3	1244	0.521	19946	8859	
Q4A3	1229	0.525	19831	9685	
Q1A4	1281	0.511	20506	9416	
Q2A4	1224	0.529	19807	10615	
Q3A4	1217	0.525	19294	8883	
Q4A4	1249	0.541	20114	9395	

Table 1: Material properties obtained from the tensile test

Gauge Length	2.00	in
Theoretical Yield Strength	21000	psi
Theoretical YS range	18100 - 29000	psi
Theoretical % elongation @ break	25	%
Theoretical % elongation range @ break	>= 16	%
Theoretical elastic modulus	10300	ksi

Table 2: Theoretical values for Al 5083-O from Matweb.

## Conclusion

In Summary, all tested samples fell between the theoretical yield strength range as expected and most importantly were close to the lower limit of 18100 psi which is the preferred yield strength value. Also the test was carried out with the 8500 series Instron machine capable of delivering a load of about 11200lbs at room temperature of 73°F and none of the sample showed the weakness observed in the previously tested samples.

## Acknowledgement

I would like to acknowledge the contributions of certain individuals to my success in this project. First, special thanks to my supervisor Luciano Elementi, who provided me the rare opportunity of working on two career oriented projects this summer. Also, a very big thank you to Donna Hicks and Daniel Evbota, for providing all the resources I needed for the success of this project. Finally, I want to appreciate the SIST committee for granting me the opportunity to be a part of this great internship.

## References

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## Appendix

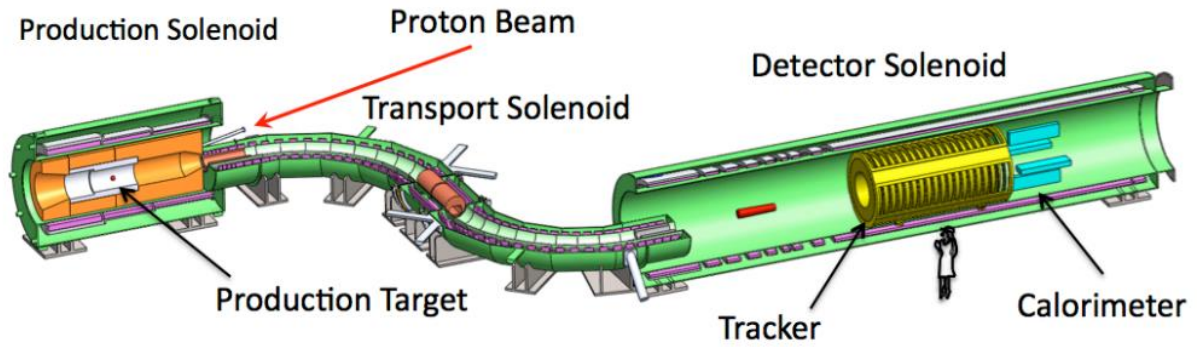


Figure 1: Magnet System of the Mu2e Experiment

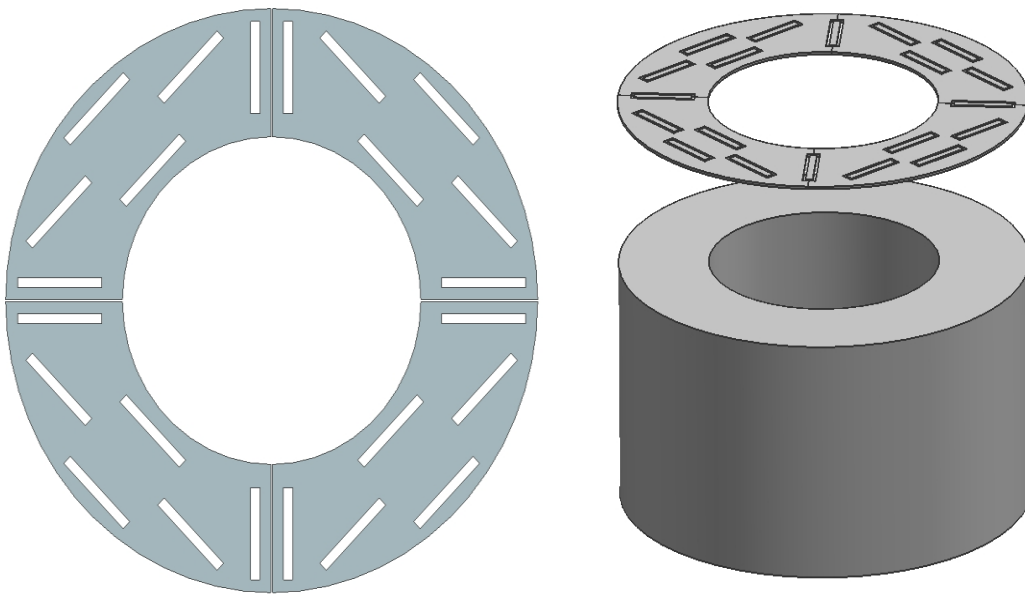


Figure 2: 8mm Slice cut from Aluminum Alloy Al 5083-O



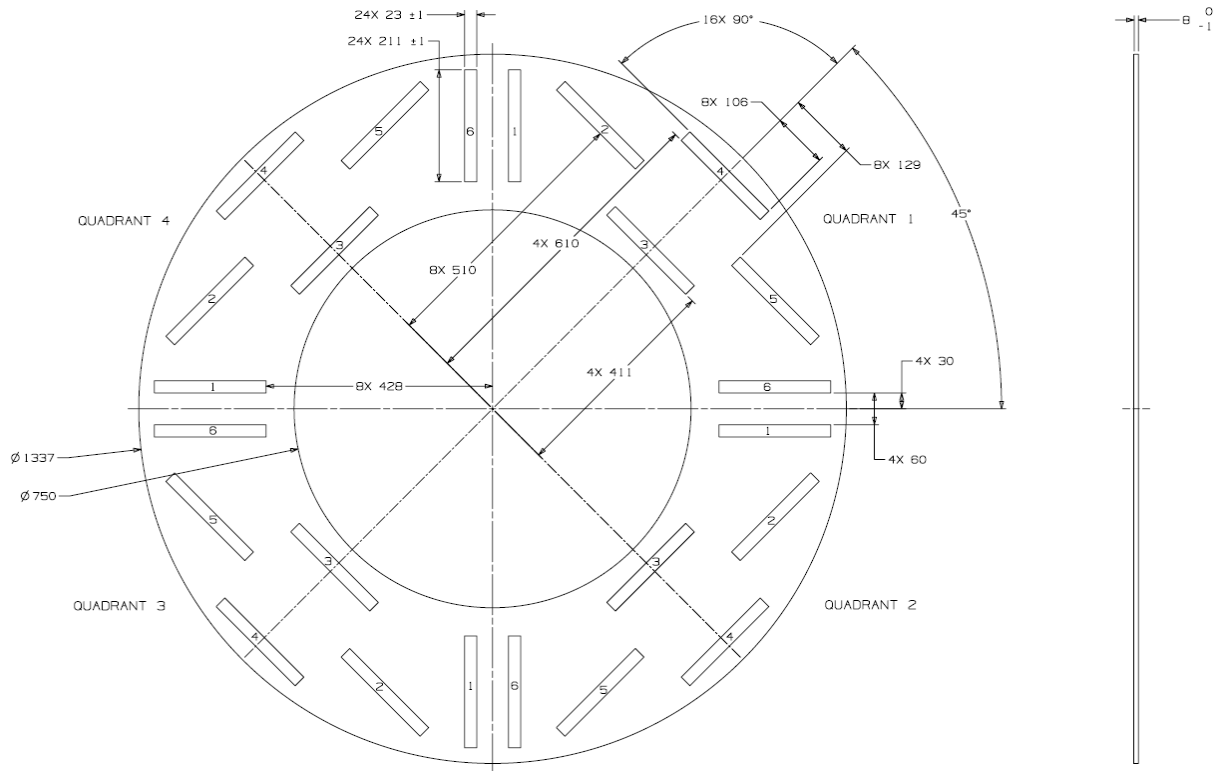


Figure 3: 2D profile of Aluminum slice.

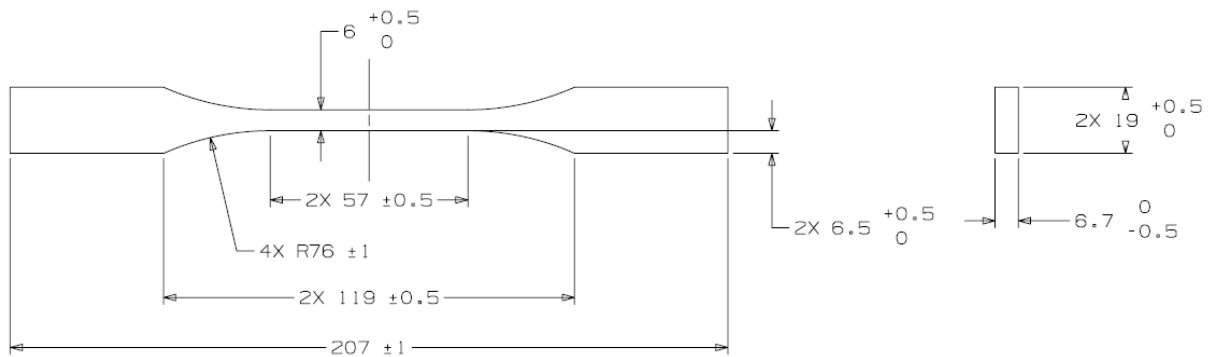


Figure 4: Test Sample and its dimensions (ASTM standard)



Figure 5: The 12 Test specimen before testing



Figure 6: The Instron Machine

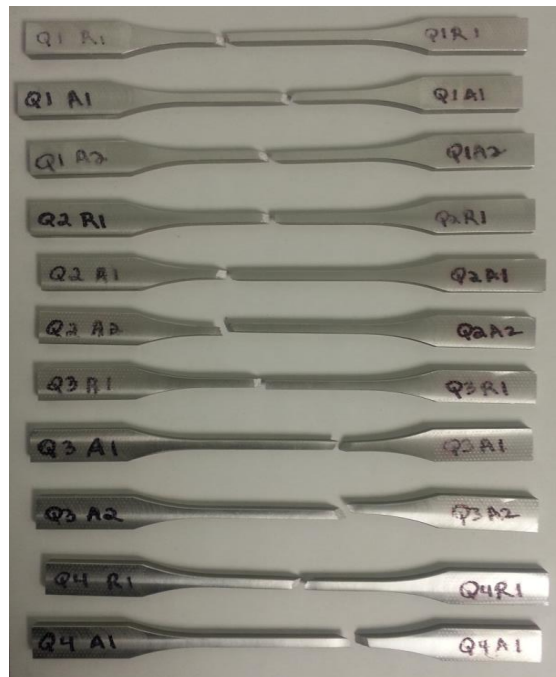


Figure 7: Destroyed Samples